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Consumable electrode – additional filler wire arc interaction control under surfacing (DE-GMAW)

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Introduction. Arc surfacing through feeding an additional filler wire heated by an additional arc burning between the filler wire and the electrode wire is considered. Under the conditions of such surfacing, the minimization of the input of the remelted substrate metal into the weld metal is studied. The research objectives are to examine the conditions providing self-regulation of this advanced arc surfacing process, and to evaluate control capabilities of the heat impact power on the metal and on the weld metal flow.

Materials and Methods. In solving a wide range of welding and surfacing tasks, it is advisable to use engineering analysis methods based on physicomathematical modeling of processes and phenomena. These include:

— self-regulation of the arc process under joint melting of the electrode and the filler wires;

— assessment of the possibilities to control the heat impact power on the metal and on the weld metal flow during the formation of the weld pool. The features of the arc surfacing of anticorrosive chromium-nickel steels on low-alloy steel are considered in the paper.

Results. New mathematical dependences are proposed that describe physical phenomena under surfacing with an arc interaction between the electrode and filler wire. A physicomathematical model of the joint melting of the electrode and filler wire is developed. It provides determining the values of the control parameters. In addition, you can find out how much heat affects the substrate from:

— heat release in the main arc,

— droplet flows of the weld electrode and filler metal,

— arc plasma radiation.

Discussion and Conclusions. It is established how the current and the lengths of the main and additional arcs are affected by the supply voltages. The feed rate of the electrode and filler wire with a diameter of 1.6 mm and 1.2 mm made of Inconel 625 alloy is determined. It is shown what thermal effect the substrate undergoes in this case. It is noted that due to the larger value of the main arc current, the diameter of the electrode wire should be larger than that of the filler wire. The heat flow in the substrate is created mainly by the flow of the weld metal droplets.

Keywords*:* physicomathematical model, arc interaction, surfacing, consumable electrode, filler wire.

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Introduction. Surfacing with materials whose characteristics differ markedly from the base metal, provides the necessary performance properties of the contact surfaces of the products. When surfacing, it is required to reduce the mixing of materials, so you need to adjust the power of the heat impact on the surface of the base metal, and the amount of melting material. In [1], the possibility of such regulation through changing the heat flow during the arc interaction of a melting electrode with an additional filler wire was first validated. Initially, this approach was used mainly in welding [2-4], and in recent years — in surfacing [5]. According to the author of the paper [6], this method of surfacing will help to provide high performance properties of the sealing and contact surfaces of pipeline fittings. However, a number of researchers have noted a factor that complicates the use of this method in welding and surfacing. They consider the major problem to be the filler wire feed control. At an insufficient feed rate, it can melt outside the molten pool, and at a high feed rate, it cannot melt. Therefore, to provide the required flow of the deposited material with a limited heat impact of the arc on the metal surface, it is necessary to accurately set the current of the additional arc burning between the wires. The working conditions, the instability of the wire feed, and the heterogeneity of their thermophysical properties also unpredictably change the melting conditions of the main electrode and the filler wire. Therefore, the surfacing process stability can be provided through using the self-regulation effect of the main and auxiliary arcs. The work objectives are to study conditions for the self-regulation of the arc process through co-melting of the electrode and filler wire, as well as to assess the possibility of heat power control for the metal and the filler metal flow.

Materials and Methods. When solving a number of problems, the use of engineering analysis methods based on physical and mathematical modeling of welding processes is challenging [7, 8]. Such models are a system of differential equations, whose boundary conditions take into account many technological factors. The equations are solved in an iterative cycle. An important advantage of this method of engineering analysis based on fundamental physical laws is the universality of the results and the possibility of using them to study the mechanisms of physical interactions in welding and surfacing processes [9]. Such phenomena include:

— self-regulation of the arc process under the joint melting of the electrode and filler wires,

— assessment of the possibility of controlling the power of thermal impact on the metal.

However, taking into account the effect of arc self-regulation, it is required to further investigate features of the joint melting of the electrode and filler wires. In addition, you need to know with what power the substrate is affected by heat from:

— heat generation in the main arc,

— droplet flows of the deposited electrode and filler metal,

— arc plasma radiation.

In this paper, we consider double-electrode gas metal arc welding, DE-GMAW, and electrode surface welding (a melting electrode and a current-carrying filler wire) in a protective gas.

Main Part. To study the mechanism of interaction between the main and additional arc between the electrode and filler wires, a physicomathematical model is required with account for the following:

— features of the melting of the electrode and filler wires,

— the effect of self-regulation of the thermal power of arcs under surfacing.

The numerical solution to the model equations in an iterative cycle provides a deeper study of the adjustment characteristics of the process and their influence on the thermal power of the surfacing.

Physical model of electrode and filler wire melting. Taking into account many significant factors, it is appropriate to use the approaches described in [10] when studying the features of self-regulation of melting of electrode and filler wires. However, the modeling space needs to be specified. Consider the refined modeling space for the melting conditions of the electrode and filler wire under the action of arcs. The first of them — *a* (Fig. 1) burns between the electrode wire 1 and the substrate 3, and the second *b* — between the electrode and the filler wire 2. In this case, in our opinion, it is suitable to feed the wire from the front of the molten pool. This will eliminate welding ("freezing") of the unfused filler wire in the solidifying metal of the tail section of the molten pool.

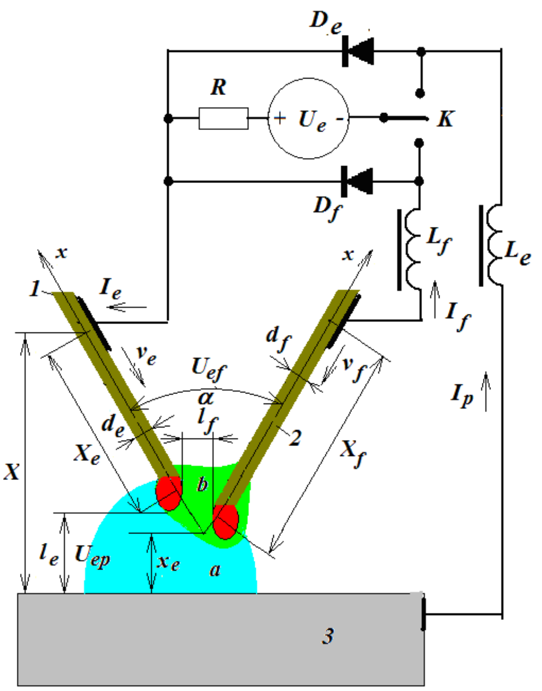

Fig. 1. Process chart of double-arc consumable electrode surfacing with an additional filler wire

To form a common plasma column of arcs *a* and *b*, the filler wire is fed at an angle α to the axis of the melting electrode *x*. This enables the axes of the filler and electrode wires to intersect at a given distance X from their current contact nozzles, and to set the distance x_e from the intersection point of the wire axes to the metal surface. In the simulation space, feed rates and wire diameters of the electrode wire v_e, d_e and the filler wire v_f, d_f are also set.

For the main arc *a,* voltage U_{ep} is given, and for the additional arc *b* — U_{ef}. These voltages are regulated by the key *K*, which redistributes voltage U_e of the power supply between the arcs. The continuity of arc currents I_e, I_f are provided by chokes L_e, L_f and closing diodes D_e, D_f. Arc currents I_e, I_f are self-adapted through a self-regulatory effect of lengths l_e, l_f of the corresponding arcs. The lengths of the electrode stickouts X_e, X_f are determined through the melting of the electrodes. The melting rates are determined by the arc currents I_e, I_f and the voltage drop in the anode regions, as well as by the heating of the stickouts by the arc currents passing through them. R — electrical resistance of the power supply.

Mathematical model of the surfacing process self-regulation. The main control action on the process is provided by the operation of the key *K*. Its closures (with a period of τ and duration of t_e, t_f) regulate the voltage on the electrodes:

$$U_{\text{ep}} = (U_e - (R_e{+}\text{R})I_e)\frac{t_e}{\tau};\, U_{\text{ef}} = \left(U_e - \left(R_f + R_e{+}R\right)I_f\right)\frac{t_f}{\tau}, \tag{1}$$

where R_e, R_f — electrical resistances of the electrode and filler wire stickouts.

In the steady-state mode, these voltages determine the arc lengths [11]:

$$l_e = \frac{1}{E}\left(U_{\text{ep}} - U_a - U_k\right);\, l_f = \frac{1}{E}\left(U_{\text{ef}} - U_a - U_k\right), \tag{2}$$

where U_a, U_k — voltage drop in the anode and cathode regions of the arc; E — potential gradient in the arc column.

It is advisable to determine the average values of the arc currents through the melting rates of the wires, which, in the steady-state mode, are equal to the rates of their supply:

$$I_f = \frac{v_f \pi \text{d}_f^2}{4U_k}\left(c\rho\left(T_k - T_{Xf}\right) + q_{LS}\right), I_e = \frac{v_e \pi \text{d}_e^2}{4U_a}\left(c\rho(T_k - T_{Xe}) + q_{LS}\right), \tag{3}$$

where T_k — temperature of electrode metal drops; $c\rho$ — heat capacity of metal of wires; q_{LS} — melting heat; T_{Xe}, T_{Xf} — preheat temperatures of wire stickouts by arc currents.

It should be taken into account that with pulse regulation, the current will change with the period τ and the amplitude:

$$\Delta I = \frac{U_e \tau}{L}. \tag{4}$$

However, with a small period of change, typical for modern power supplies, the periodic change in current can be ignored.

Current flowing through the cathode spot on the metal surface:

$$I_k = I_e - I_f. \tag{5}$$

To find out the temperature distribution along the stickout axes x of the electrode $T_e(x)$ and filler $T_f(x)$ wires, it is required to consider the dependence of the electric resistivity of the wire metal on the temperature $\rho_e(T)$ [12].

Then the temperature distribution is:

$$T_e(x) = \left(\frac{4I_e}{\pi d_e^2}\right)^2 \frac{1}{v_e c\rho}\int_0^x \rho_e\big(T_e(x)\big)\,dx,\ T_f(x) = \left(\frac{4I_f}{\pi d_f^2}\right)^2 \frac{1}{v_f c\rho}\int_0^x \rho_e\big(T_e(x)\big)\,dx. \tag{6}$$

The preheat temperature T_{Le} is determined from its values at the end of the stickout $x = X_e$

As noted in [13, 14], the temperature of the metal drops T_k entering the weld (molten) pool is determined by a combination of many factors. However, in any case, it will be in the range between the melting point T_L and the boiling point T_V of the metal:

$$T_k \approx \frac{T_V + \mathrm{T}_L}{2}. \tag{7}$$

The heat dissipation power is calculated using the following formulas.

— For the cathode arc spot:

$$P_k = U_k\big(I_e - I_f\big) \tag{8}$$

— Transferred by electrode droplets:

$$P_e = U_a I_e + c\rho T_{Xe} v_e \frac{\pi d_e^2}{4}. \tag{9}$$

— From the flow of filler wire droplets:

$$P_f = U_k I_f + c\rho T_{Xf}\, v_f \frac{\pi d_f^2}{4}. \tag{10}$$

The arc column radiation power:

$$P_{\mathrm{rad}} = E\big(I_f l_f + I_e l_e\big). \tag{11}$$

Only a part of the arc radiation reaches the surface of the substrate. Note that the radiation intensity is inversely proportional to the square of the distance from the radiation center. Assume that this center is removed from the substrate surface by the length of the main arc. Then, the power on the surface of the substrate:

$$P_r = \frac{P_{\mathrm{rad}}}{2}\iint_S \frac{dS}{r^2 + l_e^2}, \tag{12}$$

where S — surface area, r — the distance from the surface to the arc torch axis.

The numerical solution to the model equations is reduced to an iterative selection of arc currents, in which equality is achieved in all relations (Fig. 2).

Source data: metal grade and surfaced material,
dimensions X_1, X_2, x_e the surfacing mode parameters v_e, d_e, v_f, d_f, U_e, R, τ, t_e, t_f.
Material properties from the databases T_v, T_L, $c\rho$, q_{LS}, U_a, U_k, E, $\rho_e(T)$.

Initial approximation

Iterative cycle of current refinement I_e, I_f

- Calculation of temperature distribution in stickouts: $x = 0$, $T(x) = T_0$, $R_e = 0$, $R_f = 0$
- Cycle $x = x + dx$
  - $$T_e(x) = \mathrm{T}_e(x) + \left(\frac{4I_e}{\pi \mathrm{d}_e^2}\right)^2 \frac{\rho_e\big(T_e(x)\big)}{v_e c\rho}dx,\ T_f(x) = T_f(x) + \left(\frac{4I_f}{\pi d_f^2}\right)^2 \frac{\rho_e\big(T_f(x)\big)}{v_f c\rho}dx$$
  - Electric resistivity of the stickouts:
    $$R_e(x) = R_e(x) + \frac{\rho_e\big(T_e(x)\big)}{\pi d_e^2}dx,\ R_f(x) = R_f(x) + \frac{\rho_e\big(T_f(x)\big)}{\pi d_f^2}dx$$
- as long as $x < X_e$ or $x < X_f$
- Parameters of stickouts $T_{Le} = T_e(L_e)$, $T_{Lf} = T_f(L_f)$, $R_e = R_t(L_e)$, $R_f = R_f(L_f)$
- Clarification of currents
  $$I_f = \frac{1}{4}\left[3I_f + \frac{v_f \pi d_f^2}{4U_k}\big(c\rho(T_k - T_{Xf}) + q_{LS}\big)\right],\ I_e = \frac{1}{4}\left[3I_e + \frac{v_e \pi d_e^2}{4U_a}\big(c\rho(T_k - T_{Xe}) + q_{LS}\big)\right]$$

until I_e const or I_f const

Determination of process parameters: $D = k_D\big(I_e + I_f\big)^{\frac{2}{3}} + d_e$;

$$P_e = U_a I_e + c\rho T_{Xe} v_e \frac{\pi d_e^2}{4};\ P_f = U_k I_f + c\rho T_{Xf}\, v_f \frac{\pi \mathrm{d}_f^2}{4};$$

$$P_r = \frac{E}{2}\big(I_f l_f + I_e l_e\big)\iint_S \frac{dS}{r^2 + l_e^2};\ l_e = \frac{1}{E}\big(U_{ep} - U_a - U_k\big);\ l_f = \frac{1}{E}\big(U_{ef} - U_a - U_k\big).$$

Fig. 2. Algorithm for calculating the parameters of the joint melting process of electrode wires

The algorithm for calculating the parameters of the joint melting process of electrode wires presented in Fig. 2 enables to study in detail the conditions of self-regulation of the main and additional arcs under surfacing.

Research Results

Process control characteristics. Regulatory actions:

— the feed rate of the electrode and filler wires,

— the no-load voltage of the power supply,

— the relative duration of the key closures, which controls the ratio of the voltages of the main and additional arcs.

These actions determine the arc currents, their lengths, and the power distribution of the process. Additional parameters that determine the results of regulation are the wire diameters, their stickouts, and the angles between them.

The ranges of control parameters values are limited. The most important of them is the condition for the existence of an arc between the substrate and the electrode, i.e., the current $I_k = I_e - I_f > 0$ through the cathode spot on the substrate.

Accordingly, the relation should be fulfilled:

$$\frac{v_e d_e^2}{U_a} > \frac{v_f d_f^2}{U_k}. \quad (13)$$

The second critical limitation is the minimum voltage on the arcs, which provides their stable arcing in the absence of short circuits:

$$U_e \frac{t_e}{\tau} > U_a + U_k; U_e \frac{t_f}{\tau} > U_a + U_k. \quad (14)$$

In addition, it is required to provide the correct location of the vanishing point of the electrodes above the substrate surface and the deposited layer, and the absence of short circuits by the electrode metal drops, i.e., the length of the main arc should be:

$$l_e > x_e + l_f \operatorname{ctg}\frac{\alpha}{2}; x_e > d_e. \quad (15)$$

To do this, the main arc voltage should be at least:

$$U_e \frac{t_e}{\tau} > U_a + U_k + El_e. \quad (16)$$

The length of the additional arc l_f is a process parameter that provides removing the flow of additive drops from the main arc.

Influence of the control parameters on the process power. The power of the heat fluxes acting on the substrate in the sum of the heat release in the cathode spot of the main arc, the radiation power of the main and additional arcs, heat transfer by drops of the electrode and filler metal. Fig. 3 shows the effect of the feed rate of the electrode wire with a diameter of 1.6 mm made of Inconel 625 alloy on:

— current I_e of the main arc,

— power P_k, emitted in the cathode spot,

— power P_e of the heat flux drops of electrode metal,

— temperature T_e of heating the electrode stickout,

— length l_e of the main arc.

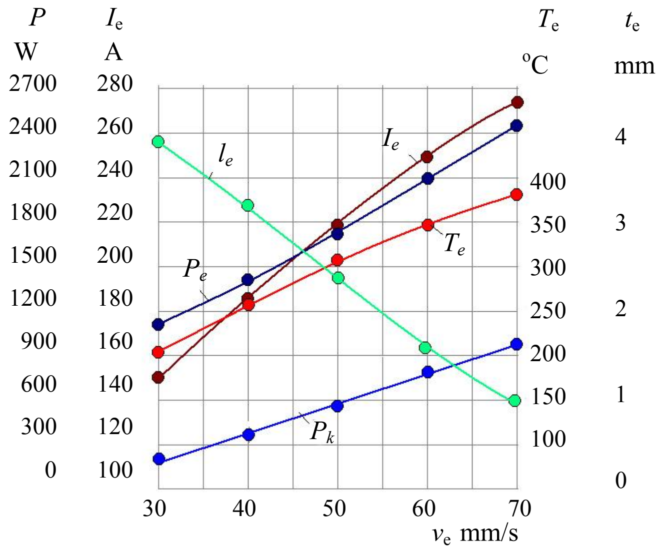

Fig. 3. Dependence of the main arc parameters on the feed rate v_e of the electrode with a diameter of d_e = 1.6 mm made of Inconel 625 alloy at stickout of l_e = 10 mm, supply voltage U_e = 32 W, duty cycle t_e/τ = 0.5, and the additional arc current I_f = 108 A

With an increase in the speed v_e of the electrode wire feed at a fixed current I_f of the additional arc, the current I_e, flowing through the electrode, increases almost in proportion to the speed. The deviation from the proportionality is explained by a noticeable increase in the temperature T_e of the electrode stickout. For the same reason, the power P_e that heats the electrode increases faster than the arc current I_e. The power P_k, released in the cathode spot on the substrate surface is almost proportional to the feed rate, but it is much less than the thermal power P_e of the droplet flow. The length l_e of the main arc decreases linearly as the electrode feed rate increases.

Fig. 4 shows the impact of the feed speed v_f of the filler wire with a diameter of 1.2 mm made of Inconel 625 alloy on:

— additional arc current I_f,

— power P_k generated in the cathode spot,

— power P_f of the heat flux drops of metal filler wire,

— temperature T_f of the heated wire stickout,

— length l_f of the additional arc.

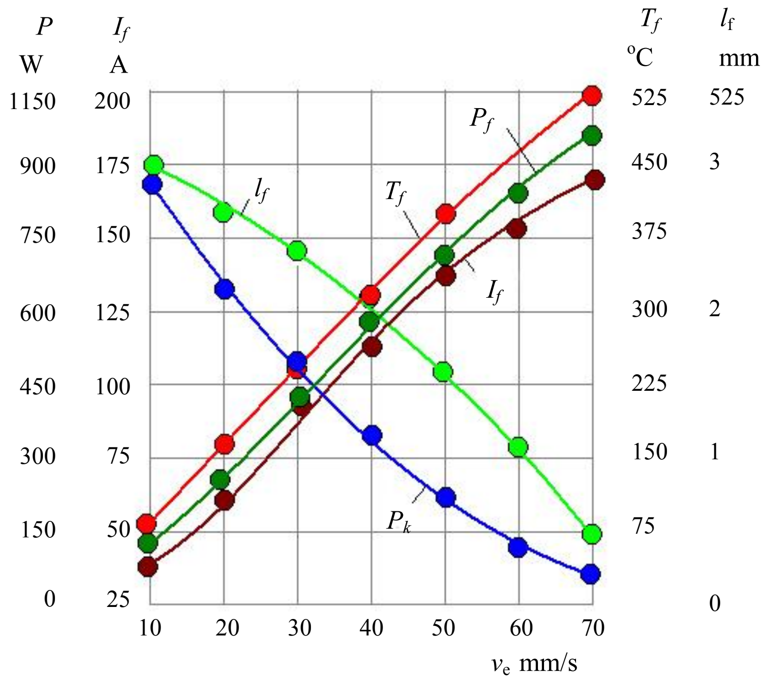

Fig. 4. Dependence of the additional arc parameters on the feed speed v_f of the filler wire with a diameter of d_e = 1.2 mm made of Inconel 625 alloy at stickout of l_e = 10 mm, supply voltage U_e = 32 W, duty cycle t_f / τ = 0.5, and the main

With an increase in the feed rate v_f of the filler wire at a fixed current I_e of the main arc, the current I_f is somewhat disproportionate to the feed rate due to a noticeable increase in the temperature T_f of the wire stickout. The power P_e, spent on heating the wire increases faster than the current I_f of the additional arc. The power P_k, generated in the cathode spot on the substrate surface, is greatly reduced through increasing the feed rate of the filler wire due to the redistribution of the main arc current to the filler wire. The thermal power P_f of the flow of the droplets from the filler wire is less than the power P_e of droplets from the electrode. The length l_f of the additional arc decreases non-linearly as the feed rate increases. This is due to the impact of the electrical resistance, which is greater in the filler wire than in the electrode stickout due to the smaller wire diameter and higher temperature T_f. The voltage of the arcs determines their length, i.e., their location above the substrate.

Fig. 5 shows how the distance between the electrode and filler wire and their distance from the substrate depend on the surfacing mode.

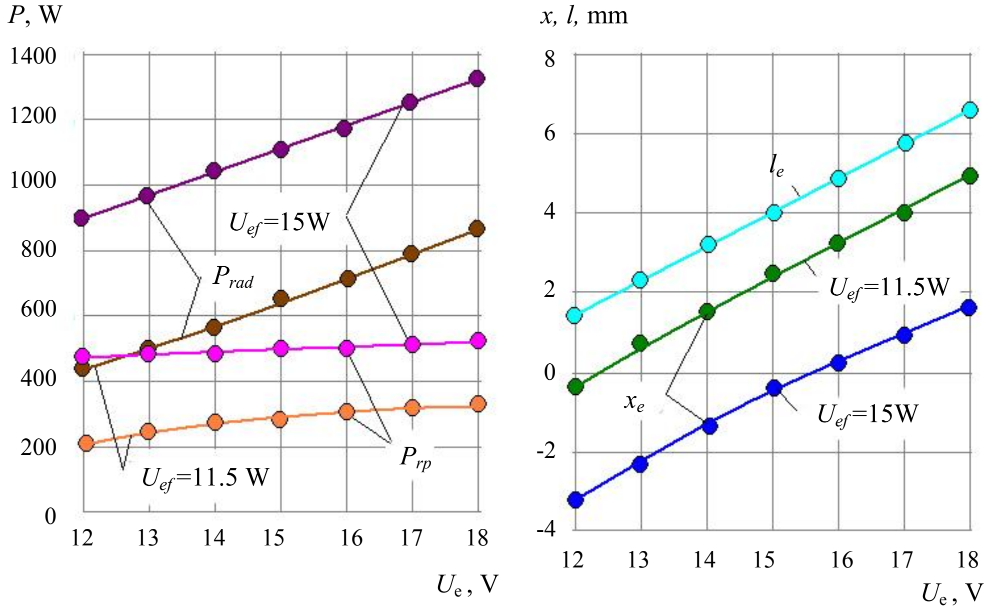

Fig. 5. Impact of the main arc voltage U_{ep} at different additional arc voltage U_{ef} on: arc radiation power P_{rad} , arc radiation power on the substrate P_{rp} , main arc length l_e, main arc length x_e from the vanishing point of the electrodes to the substrate

The minimum arc voltage (12 V) is determined from the sum of the anode and cathode voltages, as well as their minimum length. The voltage U_{ef} is set between the electrode wire and the filler wire. At the same time, an increase in the voltage U_{ep} between the electrode and the substrate increases the length l_e of the main arc, which is accompanied by an increase in the power P_{rad} of heat release in the plasma arc torch. Rising the voltage U_{ef} between the electrode and the additive increases the length l_f of the additional arc, which also increases the power P_{rad}. Some part P_{rp} of this power P_{rad} is radiated to the substrate surface. The dependence of the total power P_{rad} of the arc torch on the voltage of the main arc U_{ep} is noticeable. At the same time, a change in the power P_{rp} that heats the substrate is less significant. This is due to the removal of the arc plasma from the substrate as the length l_e of the main arc increases. The voltage of the additional arc U_{ef} affects the heating power P_{rp} of the radiation much more strongly, since the distance between the arc torch and the substrate does not depend on this voltage. Voltages U_{ep} and U_{ef} affect significantly the location of the wire vanishing point x_e, which imposes restrictions on the power supply of the arcs.

Discussion and Conclusions. Surfacing with the electrode and filler wire arc interaction enables to adjust the power consumed for melting the deposited metal and for heating the substrate. The stability of consumable-electrode arc welding is usually provided by the self-regulating effect, which equalizes the melting and feeding rates of the electrode wires when they change over a wide range. The physicomathematical model of joint melting of electrode and filler wires is developed with account for self-regulation, in which the control actions are the wire feed rates and the voltage on the welding torches, while the currents and arc lengths are the results of self-regulation. The model provides determining the values of the control parameters, as well as the power of the thermal effect on the substrate under the consumable-electrode surfacing with additional filler wire.

Based on the results of the work performed, the following conclusions can be drawn.

1. Under the consumable-electrode arc surfacing with additional filler wire, to effectively regulate the ratio between the volumes of the surfaced material and the remelted substrate, the following self-regulation should be provided:

— of the main arc between the electrode and the substrate,

— of the additional arc between the electrodes.

2. Self-regulation of the arc melting process of the electrode and filler wires is described by a system of equations. In it, the control actions are the wire feed rates and the voltages of the main and additional arcs, and the control results are the arc currents, their lengths, the distribution of heat generation power, the heat fluxes of the electrode metal droplets and the arc radiation on the substrate surface.

3. Limits are set on:

— the ratio of the parameters of the feed of the electrode and filler wire, which provide the presence of an arc between the electrode and the substrate;

— minimum voltage across arcs maintaining their stable burning in the absence of short circuits.

4.Calculations of the modes of consumable-electrode surfacing with an additional filler wire of the Inconel 625 alloy are performed. The calculations show that the process can be controlled over a wide range of wire feed rates and burner voltages.

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Claimed contributorship

S. S. Poloskov: definition of the modeling area and boundary conditions; analysis of the research results, text preparation; formulation of conclusions. V. A. Erofeev: physicomathematical model development; analysis of the research results. M. A. Sholokhov: academic advising; the text revision; correction of the conclusions.

All authors have read and approved the final manuscript.